Air Pollution and Child Mortality: A Time–Series Study in São Paulo, Brazil

Gleice M.S. Conceição,[1] Simone G.E.K. Miraglia,[1] Humberto S. Kishi,[1] Paulo H.N. Saldiva,[1] and Julio M. Singer[1,2]

[1]Laboratório de Poluição Atmosférica Experimental, Departamento de Patologia, Faculdade de Medicina da Universidade de São Paulo, São Paulo, Brasil; [2]Departamento de Estatística, Instituto de Matemática e Estatística da Universidade de São Paulo, São Paulo, Brasil

Although most available evidence relating air pollution and mortality was obtained for adults, pollution has been also associated with increased mortality in children, but in a significantly smaller number of studies. This study was designed to evaluate the association between child mortality and air pollution in the city of São Paulo, Brazil, from 1994 to 1997. Daily records of mortality due to respiratory diseases for children under 5 years of age were obtained from the municipal mortality information improvement program. Daily concentrations of sulfur dioxide (SO_2), carbon monoxide (CO), inhalable particulate matter less than 10 μm in diameter (PM_{10}), and ozone were obtained from the state air pollution controlling agency. Information on minimum daily temperature and on relative humidity were obtained from the Institute of Astronomy and Geophysics of the University of São Paulo. Statistical analysis was performed through generalized additive models considering a Poisson response distribution and a log link. Explanatory variables were time, temperature, humidity, and pollutant concentrations. The loess smoother was applied to time (in order to model seasonality) and temperature. Significant associations between mortality and concentrations of CO, SO_2, and PM_{10} were detected. The coefficients (and standard errors) of these three pollutants were 0.0306 (0.0076), 0.0055 (0.0016), and 0.0014 (0.0006), respectively. The observed associations were dose dependent and quite evident after a short period of exposure (2 days). According to the proposed model and considering the mean of the pollutant concentration during the period of the study, the estimated proportions of respiratory deaths attributed to CO, SO_2, and PM_{10}, when considered individually, are around 15, 13, and 7%, respectively. *Key words:* air pollution, children, epidemiology, mortality, respiratory diseases. — *Environ Health Perspect* 109(suppl 3):347–350 (2001).
http://ehpnet1.niehs.nih.gov/docs/2001/suppl-3/347-350conceicao/abstract.html

The association between air pollution and mortality has been clearly established in recent years, even in nonepisodic events. This association has been reported across a wide range of concentrations, exhibiting little evidence of a safe threshold level. The most robust associations between pollution and mortality were obtained with the inhalable particulate matter less than 10 μm in diameter (PM_{10}), which is derived from combustion processes (*1–7*).

Although most of the available evidence relating air pollution and mortality was obtained for adults, pollution has also been associated with increased mortality in children but in a significantly smaller number of studies. In 1991 Penna and Duchiade reported a significant association between total suspended particulates and mortality due to pneumonia in children in the metropolitan area of Rio de Janeiro, Brazil (*8*). In 1992, using a similar approach, Bobak and Leon found a significant association between postneonatal mortality and PM_{10} levels in the Czech Republic (*9*). More recently, Woodruff et al. also found a significant relationship between postneonatal infant mortality and particulate pollution in the United States (*10*). These three studies relating air pollution and child mortality were obtained via multivariate models using mortality data aggregated over long periods as the dependent variable.

Daily time–series analysis is commonly used to evaluate short-term effects of air pollution on mortality. Such an approach is quite sensitive in detecting acute effects of air pollution on health, as the corresponding estimates are less affected by confounding variables that may be present when data obtained during large periods of time are aggregated. For instance, it is difficult to imagine that the quality of medical care may exhibit synchronous variations with air pollution. Daily time–series analysis is not routinely employed in mortality studies for children, probably because of the low number of deaths recorded in locations where frequent measurements of air pollution are available. In São Paulo, Brazil, however, studies using time–series analysis detected positive associations between gaseous components of urban air pollution and child mortality (*11*) and intrauterine mortality (*12*). A similar study was carried out in Mexico City, Mexico, and a significant association between children mortality and $PM_{2.5}$, (inhalable particulate matter less than 2.5 μm in diameter) nitrogen dioxide (NO_2), and ozone (O_3) was detected (*13*). Considering the importance of these findings and the lack of information on the air pollution effects on mortality in this age group, we decided to explore this subject further by performing a larger time–series analysis with more recent data. More specifically, we evaluated the association between child mortality and air pollution in the city of São Paulo from 1994 to 1997.

Material and Methods

Mortality Data

Daily records of mortality for children under 5 years of age in São Paulo were obtained from the municipal mortality information improvement program (PRO-AIM) from January 1994 to December 1997. Every death in the city is registered in the PRO-AIM files. In São Paulo the death certificate is mandatory, and by law it must be registered in the municipal office. The PRO-AIM collects those death certificates and submits them to quality control procedures (such as calling the attending physicians in the case of dubious information).

Mortality due to congenital malformations, caused by neonatal events, or due to nonnatural causes were excluded. Mortality due to respiratory diseases was defined in accordance with the *International Classification of Diseases* (*ICD*). It was adopted in the *ICD-9* (*14*), codes 460 to 519, from 1994 to 1995 and in the *ICD-10* (*15*), codes J00 to J99, from 1996 to 1997.

Pollution and Weather Data

São Paulo has a state air pollution controlling agency (CETESB) with 11 monitoring stations that provide daily records of sulfur dioxide (SO_2) (24-hr mean), carbon monoxide (CO) (greatest 8-hr moving average), PM_{10} (24-hr mean), and O_3 (24-hr peak) concentrations. The measurements are based in different time intervals mostly because the health standards required by Brazilian legislation were defined using those time windows.

However, not all the stations provide measurements of all the pollutants. Because the trend and the variability of the pollutant concentrations are similar for all stations (that

Address correspondence to G.M.S. Conceição, R: Trajano Reis, 137, Apto 71-B, Jardim das Vertentes, São Paulo-SP, 05541-030 Brazil. Telephone: 55 11 3064 2744. Fax: 55 11 3064 2744. E-mail: gleice@usp.br

This work was supported by the following Brazilian institutions: Fundação de Amparo à Pesquisa do Estado de São Paulo, Conselho Nacional do Desenvolvimento Cientifico e Technológico, Financiadora de Estudos e Projetos/Programa de Apoio a Núcleos de Excelência, and Laboratório de Investigação Médica do hospital das Clínicas da Faculdade de Medincia da Universidade de São Paulo. The authors thank S. Bremner from St. George's Hospital Medical School, University of London, London, U.K., for providing the computer program for the autoregressive models.

Received 3 July 2000; accepted 9 April 2001.

is, when pollution levels increase in the central area, there is a proportional increase in the suburbs), the values obtained at stations with available records were averaged and considered indicative of the citywide status.

Unfortunately, the NO_2 monitors of CETESB presented significant problems during the period of analysis (860 missing points), so NO_2 data were not included in the present analysis.

Information on daily temperature (minimum) and relative humidity were obtained from the Institute of Astronomy and Geophysics of the University of São Paulo.

Statistical Modeling

Statistical analysis was performed through generalized additive models, which consider nonparametric smooth functions of the explanatory variables (*16*), a Poisson response distribution, and a log link. Explanatory variables were time, temperature, humidity, the number of nonrespiratory deaths, and pollutant concentrations. The analysis strategy consisted of modeling first seasonality, trends, and weather variables before including the pollutant concentrations.

According to the *ICD-10*, some respiratory diseases such as pneumonia and bronchopneumonia are now accepted as complications of other diseases; hence, they are less frequently included as the basic cause of the death. As this might result in a reduction of the mean number of respiratory diseases, we included appropriate controls in the model. In particular, a nonparametric function, the loess smoother (*16*), was applied to time to control the seasonality as well as an eventual reduction in the mean number of respiratory deaths due to *ICD* versions.

The loess smoother was also applied to temperature. The smoothing parameters (12 and 5% for time and temperature, respectively), were selected on the basis of the scatterplots smoothing of their respective partial fitted values. Because the relation between mortality and humidity presented a linear behavior, no smoothing for humidity was used in the final model. We investigated the effect of weather variables recorded on the same day, lagged by 1 and 2 days as well as 2-day moving averages. The best fit was obtained when considering the values of the second previous day for temperature and the concurrent day for humidity. In the last step, we added the pollutant concentrations individually to the model, either considering their values at the concurrent day, lagged by 1 to 3 days or moving averages from 1 to 5 days. The best fit was obtained when the values of the second previous day for CO, SO_2, and PM_{10} were considered. The concurrent day record was chosen for O_3, as none of the transformed variables (lags or moving averages) were significant for this pollutant. The complete model may be expressed as

$$\log[E(\text{respiratory deaths})] = \alpha + L_1(\text{time}) + L_2(\text{minimum temperature}) + \beta_1 \times \text{humidity} + \beta_2 \times \text{nonrespiratory deaths} + \beta_3 \times \text{pollutant concentration} \quad [1]$$

where the functions L_1 and L_2 are estimated using the loess smoother.

Models in which dummy variables were used to indicate categories based on quintiles of the pollutant concentrations (instead of the continuous pollution variable) were used to verify a possible dose-dependent behavior of the relative risk.

Models were refitted with adjustments for autocorrelation, following the methods developed by Zeger (*17*). Autoregressive parameters up to order 4 were estimated, and just the significant terms were retained in the model.

To evaluate the sensitivity of the pollutant concentration coefficients to the different variables included in the model, we fitted several models for different sets of the explanatory variables.

In addition to the above modeling procedures, we refitted the models without smoothing functions using *a*) maximum likelihood with a Poisson response and a log link as in the initial approach (*18*), and *b*) ordinary least squares with a log-transformed response. In the aforementioned models, seasonality and temperature were considered by means of independent dummy variables for month of the year and years of the study, as well as different functions of temperature and humidity.

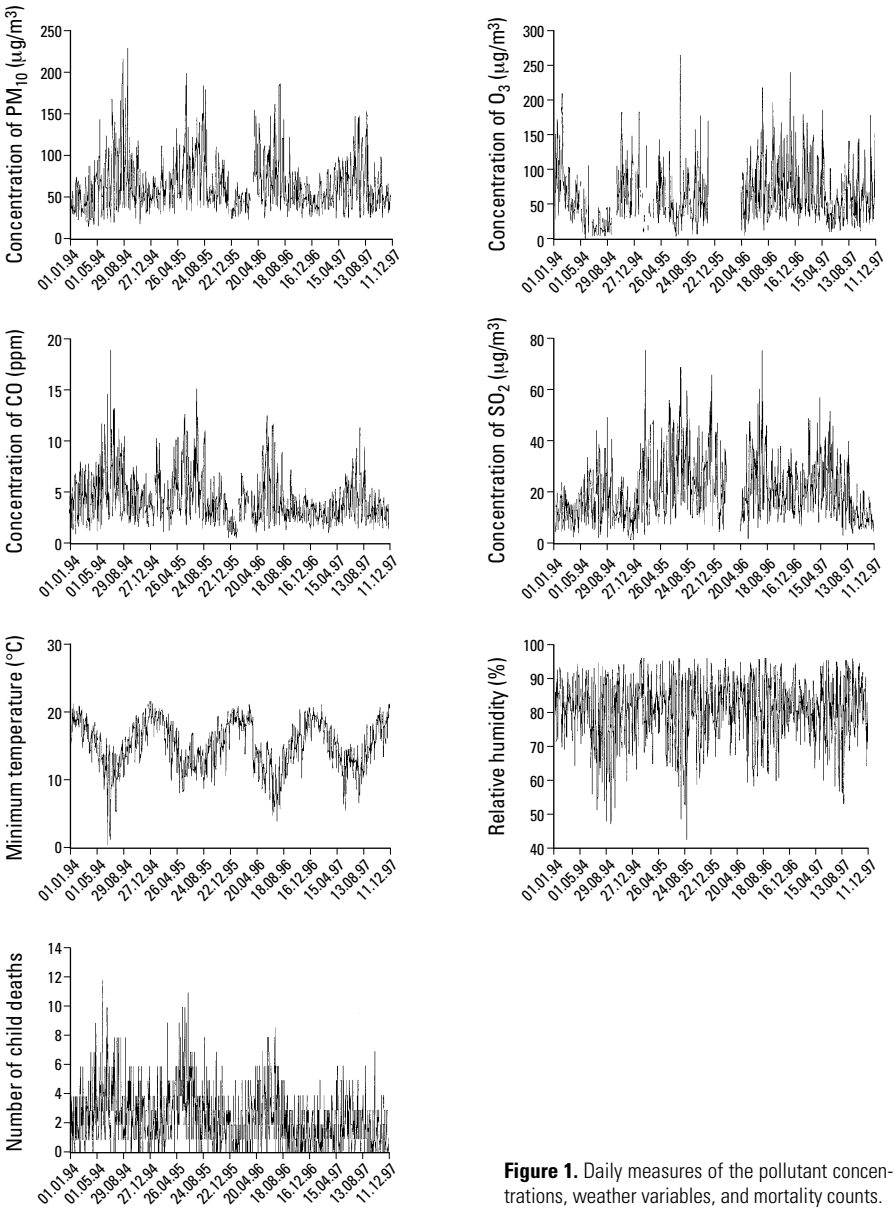

Figure 1. Daily measures of the pollutant concentrations, weather variables, and mortality counts.

Results

Figure 1 presents the daily pollutant concentrations, weather variables, and mortality counts during the period of study. Summary measures for these variables are presented in Table 1.

Mortality counts decreased continuously during the period under investigation. There were a great number of missing pollutant data for the first 3 years, especially for O_3 (22% of total observations), whereas PM_{10}, CO, and SO_2 had missing data in 3, 7, and 4% of the days, respectively.

There were moderate significant correlations (from 0.44 to 0.60) among PM_{10}, SO_2, and CO. Ozone did not present a strong correlation with the other pollutants (–0.12 to 0.13), probably because it is derived from photochemical reactions.

Figure 2 shows the estimated nonparametric functions of time and temperature, under the model represented in Equation 1. The seasonal pattern in mortality is evident, and the function also captures decreasing behavior through the years. According to the data, mortality increases as temperature decreases, and there is a plateau between 10 and 15°C.

Significant associations between mortality due to respiratory diseases and concentrations of CO, SO_2, and PM_{10} measured 2 days before death were observed, as shown in Table 2. No significant association with O_3 was observed. When the four pollutants were included in the same model, only CO remained significant; SO_2 became marginally significant.

Using the estimates in Table 2 for pollutants individually included in the model, we found it is possible to estimate the relative risk of mortality for the average concentration of each pollutant during the time of study, using the relationship ($e^{coefficient \times pollutant\ mean\ concentration} - 1$), which is around 15, 13, and 7% for CO, SO_2, and PM_{10} respectively.

Table 3 shows the coefficients for the pollutants significantly associated with mortality (CO, SO_2, and PM_{10}) in Poisson regression models with different controlling variables. Explanatory variables were progressively added: model 1 contains only the pollutant; model 2 included the nonparametric function of time; model 3 included temperature and humidity, etc. The pollutant coefficients were sensitive to the terms included in the model, suggesting that part of the effect estimated in model 1 may be due to seasonal factors or confounding variables. In model 4 we added the number of nonrespiratory deaths to control for other possible events, but this did not change the estimated coefficients relating pollution to mortality. In model 5 we adjusted autoregressive parameters, and PM_{10} became only marginally significant ($p < 0.10$).

Table 1. Mean (and standard deviation) for mortality data, pollutant concentrations, and weather variables.

	Time (year)				
	1994	1995	1996	1997	Total
Mortality counts					
Total	14.1 (3.9)	13.3 (3.9)	12.7 (3.7)	12.2 (3.6)	13.1 (3.9)
Respiratory	3.0 (1.9)	2.8 (2.0)	2.1 (1.7)	1.6 (1.3)	2.4 (1.8)
Other causes	11.1 (3.5)	10.5 (3.4)	10.5 (3.3)	10.5 (3.3)	10.7 (3.4)
Pollutants					
PM_{10} (μg/m^3)	67.0 (36.4)	73.8 (30.8)	63.8 (30.1)	60.3 (25.2)	66.2 (31.2)
SO_2 (μg/m^3)	14.9 (7.4)	27.5 (12.8)	23.0 (11.2)	19.6 (10.3)	21.0 (11.5)
CO (ppm)	5.1 (2.4)	5.1 (2.4)	3.9 (2.0)	3.7 (1.6)	4.4 (2.2)
O_3 (μg/m^3)	57.0 (39.4)	60.7 (35.4)	76.3 (41.5)	63.0 (33.5)	63.8 (37.9)
Weather variables					
Minimum temperature (°C)	15.3 (3.5)	15.3 (3.1)	15.0 (3.9)	15.4 (3.2)	15.2 (3.4)
Relative humidity (%)	79.5 (9.7)	80.5 (9.7)	82.3 (7.6)	81.2 (8.0)	80.9 (8.9)

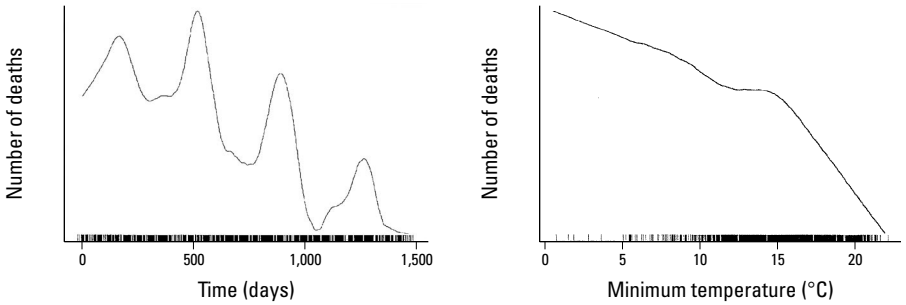

Figure 2. Smoothed plots of the number of deaths versus time and temperature, from the adjusted generalized additive model. Each vertical line represents one observation.

Table 2. Estimates for each pollutant when included individually and together in a model controlled for seasonality, temperature, relative humidity, and nonrespiratory deaths.

	Individually			Together		
Pollutants	Coefficients	Standard error	*p*-value	Coefficients	Standard error	*p*-value
CO (ppm)	0.0306	0.0076	< 0 .01	0.0259	0.0116	0.03
SO_2 (μg/m^3)	0.0055	0.0016	< 0.01	0.0045	0.0025	0.07
PM_{10} (μg/m^3)	0.0014	0.0006	0.01	–0.0008	0.0010	0.45
O_3 (μg/m^3)	0.0004	0.0006	0.46	0.0005	0.0006	0.37

Table 3. Coefficient (and standard error) for each pollutant in models with different explanatory variables.

Model specification	PM_{10}	SO_2	CO
1: Pollutant concentration	0.0043** (0.0006)	0.0070*** (0.0017)	0.0827*** (0.0077)
2: 1 + loess(time)	0.0015*** (0.0005)	0.0057*** (0.0015)	0.0285*** (0.0074)
3: 2 + loess(temperature) + humidity	0.0014** (0.0006)	0.0056*** (0.0016)	0.0309*** (0.0076)
4: 3 + nonrespiratory counts	0.0014** (0.0006)	0.0055*** (0.0016)	0.0306*** (0.0076)
5: 4 + autorregressive parameters	0.0016* (0.009)	0.0068*** (0.0024)	0.0292** (0.0118)

*$p < 0.10$. **$p < 0.05$. ***$p < 0.01$.

Figure 3 shows the relative risk for categories of CO, SO_2, and PM_{10}, indicating an increase in the risk of mortality around 20–30% in the most polluted days (when compared to the less-polluted days), suggesting a dose-dependent behavior.

Finally, using dummy variables instead of the smoothing function for controlling seasonality, as well as the use of ordinary least-squares models, did not substantially change the observed associations.

Discussion

This study showed a significant association between respiratory mortality in children and daily levels of CO, SO_2, and PM_{10} in São Paulo, Brazil. Using different models, we observed that the associations with these pollutants were significant even after terms for seasonal variation and weather were included or autocorrelation (except for PM_{10}) was considered. In addition, no association between air pollution and nonrespiratory deaths was observed. The above results are consistent with those of our previous study of child mortality due to respiratory diseases and air pollution (*11*). In the previous study, we used a 1-year time–series analysis and considered NO_x in the model. In the present work, a 4-year time–series analysis disclosed different pollutants exhibiting a significant effect on child mortality.

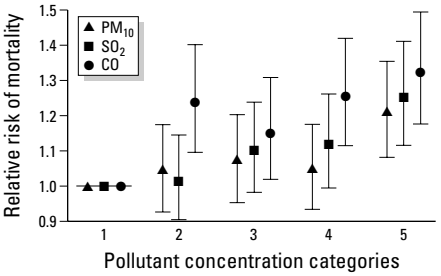

Figure 3. Relative risk of child mortality according to the categories of pollutant concentration estimated through models controlled for seasonality, temperature, relative humidity, and nonrespiratory deaths.

It is important to note that the statistical modeling of the present study is significantly more sophisticated than that considered in our study of 1994, as different options were employed. In addition, an extended period of observation was considered in the present analysis. These two factors increased the power of our more recent study, further clarifying the possible role of air pollution in promoting acute adverse effects.

The change in *ICD* versions did not influence the results. Note there was a decrease in the number of deaths from 1995 to 1996 (when *ICD-10* was adopted), but also from 1996 to 1997 (in this case, the decrease is even bigger), making it difficult to attribute such a difference to the change in *ICD* versions (Figure 2). Using the loess function, it is difficult to detect whether there are significant differences in mortality among the years of study, as that is a nonparametric function. However, if we adopt an alternative approach without smooth functions (including 12 dummy variables representing each month and 4 dummy variables representing the years of the study instead of the loess function) in the model, significant coefficients ($p < 0.01$) are obtained for 1996 and 1997, suggesting that mortality is decreasing along time of observation. The estimated coefficients (and standard errors) were –0.057 (0.046), –0.346 (0.050), and –0.619 (0.054) for 1995, 1996, and 1997, respectively. The reason for this decrease is difficult to determine within the scope of this study. It probably reflects the improvement of health policy measures adopted in São Paulo.

The present study confirms our previous observations that the gaseous fraction of urban air pollution strongly affects children's health in São Paulo (*11,12*). The effects of gaseous pollutant were even more robust than those observed for PM_{10}, which is in accordance with our previous time–series studies. In fact, it is plausible that gaseous pollutants (CO and SO_2) represent proxy variables for automotive emissions. These are intrinsic limitations of ecologic studies that do not adequately address the isolated effects of components of the complex mixture of pollutants present in the air of large towns. Despite the foregoing limitations to isolating a single agent responsible for the observed effects, this study, combined with our previous data, indicates that significant associations between child mortality and the gaseous fraction of pollution are repeatedly identified in São Paulo.

Unfortunately, our air pollution monitoring system does not provide measurements on $PM_{2.5}$, as considered by Loomis et al. (*13*) in Mexico City, although that study also suggested that a gaseous pollutant (NO_2) affects mortality.

The association between pollution and child mortality was significant only for respiratory deaths, as previously reported (*11*). In fact, the addition of nonrespiratory deaths did not change appreciably the estimated coefficients relating pollution with mortality. The same specificity of the effects of air pollution on children's health was observed in previous morbidity studies (*19,20*). Probably, the greater susceptibility of children to develop respiratory diseases compared to the health scenario of adults (with previous chronic cardiovascular diseases, for instance) induces an almost pure respiratory effect of pollution on child health.

In conclusion, this study showed a robust association between air pollution and respiratory mortality in children in São Paulo. This result is coherent with previous child mortality data (*11–13*) and indicates that air pollution in São Paulo represents a serious public health problem.

References and Notes

1. Dockery DW, Schwartz J, Spengler JD. Air pollution and daily mortality: associations with particulates and acid aerosols. Environ Res 59:362–373 (1992).
2. Pope CA III, Schwartz J, Ranson MR. Daily mortality and PM_{10} pollution in Utah Valley. Arch Environ Health 47:211–217 (1992).
3. Spix C, Heinrich J, Dockery D, Schwartz J, Völksch G, Schwinkowski K, Cöllen C, Wichmann HE. Air pollution and daily mortality in Erfurt, East Germany, 1980-1989. Environ Health Perspect 101:518–526 (1993).
4. Schwartz J. Air pollution and daily mortality: a review and meta-analysis. Environ Res 64:36–52 (1994).
5. Saldiva PHN, Pope CA III, Schwartz J, Dockery DW, Lichtenfels AJFC, Salge JM, Barone IA, Böhm GM. Air pollution and mortality in elderly people: a time-series study in São Paulo, Brazil. Arch Environ Health 50:159–163 (1995).
6. Anderson HR, Leon AP, Bland JM, Bower JS, Strachan DP. Air pollution and daily mortality in London: 1987-92. Br Med J 312:665–669 (1996).
7. Schwartz J, Dockery DW, Neas LM. Is daily mortality associated specifically with fine particles? J Air Waste Manag Assoc 46:927–939 (1996).
8. Penna MLF, Duchiade MP. Air pollution and infant mortality from pneumonia in the Rio de Janeiro metropolitan area. Bull Pan Am Health Organ 25:47–54 (1991).
9. Bobak M, Leon DA. Air pollution and infant mortality in the Czech Republic, 1986-88. Lancet 340:1010–1014 (1992).
10. Woodruff TJ, Grillo J, Schoendorf KC. The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States. Environ Health Perspect 105:608–612 (1997).
11. Saldiva PHN, Lichtenfels AJFC, Paiva PSO, Barone IA, Martins MA, Massad E, Pereira JCR, Xavier VP, Singer JM, Böhm GM. Association between air pollution and mortality due to respiratory diseases in children in São Paulo, Brazil: a preliminary report. Environ Res 65:218–225 (1994).
12. Pereira LAA, Loomis D, Conceição GMS, Braga ALF, Arcas RM, Kishi H, Singer JM, Böhm GM, Saldiva PHN. Association between air pollution and intrauterine mortality in São Paulo, Brazil. Environ Health Perspect 106:325–329 (1998).
13. Loomis D, Castillejos M, Gold DR, McDonnel W, Borja-Arbuto VH. Air pollution and infant mortality in Mexico City. Epidemiology 10(2):118–123 (1999).
14. WHO. International Classification of Diseases, 9th Revision. Geneva:World Health Organization, 1977.
15. WHO. International Classification of Diseases, 10th Revision. Vol 1. Geneva:World Health Organization, 1993.
16. Hastie T, Tibshirani R. Generalized Additive Models. London:Chapman and Hall, 1990.
17. Zeger SL. A regression model for time series of counts. Biometrika 75:621–629 (1988).
18. Dobson AJ. An Introduction to Generalized Linear Models. 2nd ed. London:Chapman and Hall, 1990.
19. Braga ALF, Conceição GMS, Pereira LAA, Kishi H, Pereira JCR, Andrade MF, Gonçalves FLT, Saldiva PHN, Latorre MRDO. Air pollution and pediatric respiratory admissions in São Paulo, Brazil. J Environ Med 1:95–102 (1999).
20. Lin CA, Martins MA, Farhat SCL, Pope CA III, Conceição GMS, Anastácio VM, Hatanaka M, Andrade WC, Hamaue WR, Böhm GM, et al. Air pollution and respiratory illness of children in São Paulo, Brazil. Paediat Perinat Epidemiol 13:475–488 (1999).